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ESTIMATING THE DEEP SPACE NETWORK MODIFICATION COSTS TO PREPARE FOR FUTURE SPACE MISSIONS BY USING MAJOR COST DRIVERS

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Abstract

This paper develops a cost model to do long range planning cost estimates for Deep Space Network (DSN) support of future space missions. The paper focuses on the costs required to modify and/or enhance the DSN to prepare for future space missions. The model is a function of eight major mission cost drivers and estimates both the total cost and the annual costs of a similar future space mission. The model is derived from actual cost data from three space missions: Voyager (Uranus), Voyager (Neptune), and Magellan. Estimates derived from the model are tested against actual cost data for two independent missions, Viking and Mariner Jupiter/Saturn (MJS).

Key Words: Cost Model, Tracking Network, Long-Range Planning, Cost Drivers.

1. INTRODUCTION

1.1 Project Objectives

The objective of this study is to develop a model that can be used in the early planning stages to estimate the cost to modify and/or enhance the DSN to prepare for future space mission support. Ongoing costs to operate and maintain the DSN are not included. The proposed model captures the major cost drivers of a mission such as its use of an Uplink (U/L), Downlink (D/L), Very Long Base Interferometry system (VLBI), etc. The proposed model gives cost estimates that are functions of the cost drivers and duration of a project, as demanded by its unique mission. The results of this study expand on previous cost modeling that was cost driver and mission independent. The previous work could be used in the very earliest stages of cost estimating, before the cost drivers and unique mission characteristics are defined [1,2]. The present study focuses on major cost drivers that make up the total cost of a project. In so doing, the total estimated project preparation cost will reflect only those cost drivers that pertain to that particular project, and thus a more project sensitive cost estimate is achieved. This paper is based on work previously described [3,4].

1.2 The Deep Space Network (DSN)

The National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) is a multimission telecommunications and radio metric data facility used to support NASA's exploration of space, research in space science, and advanced technology investigations. The Network has facilities located in North America, Europe and Australia. The Network basic services are: (1) reception of telemetry from spacecraft; (2) transmission of commands to spacecraft; (3) measurement of radio metric data for spacecraft navigation; and (4) radio science measurements.

1.3 Overview of Paper

The purpose of this work is to develop cost models that can be used for long-range planning purposes. The first model we develop is called Model A and it helps us estimate the total cost. The second model we develop is called Model B and it helps us estimate how the total costs are distributed on an annual basis over the life of the expenditures. Both models are developed based on data from 3 projects - Voyager (Uranus), Voyager (Neptune), and Magellan. The total cost obtained from each model is then checked using data from two other independent projects, MJS and Viking. However, the time profile results from Model B are not checked with these two independent projects because the actual annual detailed data is no longer available. As future data is collected at JPL (Jet Propulsion Laboratory of the California Institute of Technology), both models will be continually checked against the actual data.

In Section 2, we define the cost drivers that are required to prepare the DSN to support future space missions. Then we summarize the methodology for collecting the cost data and the cost history. The total mission cost drivers model (Model A) is developed in this section. The model is back tested against the three missions Voyager - Uranus, Voyager - Neptune and Magellan, and an example is given to show how to use the model. In Section 3, the cost drivers time profile

model (Model B) is developed. The model is back tested against the three missions and an example is given to show how to use the model. In Section 4, as an 'external' check we compare model A to two independent projects: MJS and Viking.

2. DEVELOPMENT OF COST DRIVERS MODELS

2.1 Definition of Cost Drivers

1. M/O: Maintenance & Operations Costs - These are initial entry and management costs for the project: e.g., funding for M&O network operations, network operations project support, and the Tracking Data System (TDS) manager .
2. D/L: Downlink Frequency - These are costs of adding new receiver, antenna and microwave capability to the DSN: new downlink frequency, additional performance capability to the existing receivers, antennas and microwave, increasing the number of channels provided by the existing antenna, receivers and microwave, etc.
3. U/L: Uplink Frequency - These are costs of adding new transmitter, antenna and microwave capability to the DSN: new uplink frequency, additional performance capability to the existing transmitters, antennas and microwave, such as higher power, increased phase stability, etc.
4. TEL: Telemetry Upgrade - These are costs of upgrading the telemetry and signal processing equipment; adding new technical capability, adding to the monitor and control capability, providing new techniques such as baseband combining for antenna arrays, etc.
5. G/T: Antenna Gain/Noise Temperature - These are the costs of upgrading the ratio of antenna gain to the receiving system noise temperature (G/T). This is a figure of merit for a telecommunications receiving system. Included are costs of providing new antennas, enlarging existing antennas, providing new/improved low-noise microwave amplifiers, providing antenna arrays, etc.
6. R/M: Radio Metric Accuracy Upgrade - These are costs associated with upgrading the accuracy with which the spacecraft location can be measured. This includes upgrades to the data system equipment, improving DSN station location accuracy, improving

time synchronizing calibration throughout the network stations, etc.

7. R/S: Radio Science Upgrade - These are costs associated with upgrading the DSN radio science performance. These include adding new and/or improved receivers, data processing and recording equipment, improved frequency and timing equipment/ calibration, etc.

8. VLBI: Very Long Baseline Interferometry System (VLBI) - These are costs of implementing a new complete VLBI equipment for both 34m Wide Channel Bandwidth (WCB) and 70m Narrow Channel Bandwidth (NCB) systems. Included are receivers, low-noise amplifiers, support for Radio Source Catalog and Universal Time Engineering.

9. OTH: Other - These costs are for any miscellaneous tasks not fitting into one of the above cost driver categories. See section 2.3 for further details.

2.2 Data Collection and Summary

The annual cost obligations used in this paper are taken from Telecommunications and Data Acquisition (TDA) Work Authorization Documents (WAD Obligations Performance Reports), and do not include Construction of Facilities (CofF) costs, spacecraft costs, transportation costs and/or other logistics costs.[5] All costs used in this report are adjusted for inflation to 1987 dollars using the NASA Inflation Index. The costs for the following three projects Voyager - Uranus, Voyager - Neptune, and Magellan and the typical cost driver values are shown in Table 1. The duration of the preparation costs considered in this report are: 1982 through 1986 for Voyager (U), 1985 through 1988 for Voyager (N), and 1985 through 1988 for Magellan [1,2]. Extracting the modifications and/or enhancement cost data from the TDA Work Authorization Documents was a time consuming task. It took about one work year and numerous consultations with appropriate specialists to decide which costs were modifications and/or enhancements, and to allocate these costs to the appropriate cost drivers.

2.3 Development of the Model A: The Total Mission Cost Drivers Model

We propose that the total cost can be estimated by the summation of the typical cost driver values

Table 1. Preparation cost drivers for three missions, and typical cost-driver values, 1987 \$K^a

Cost Drivers	Missions			Typical Cost-Driver Value
	Voyager (U)	Voyager (N)	Magellan	
M/O	955	677	634	755
D/L	2,647	6,566	2,211	3,808
U/L	[700]	0	8,947	8,947
TEL	10,357	[1,134]	15,445	12,901
G/T	17,795	21,008	0	19,402
R/M	2,032	580	[33]	1,306
R/S	1,374	5,484	[46]	3,429
VLBI	0	[601]	4,436	4,436
Other	700	1,735	849	1,095
Total	35,860	36,050	32,522	56,079

^aThe bracketed numbers are discussed in Section 2.3.

given in Table 1 that are relevant to the modifications and enhancements to prepare for a future mission. The typical cost driver value in the model is an effective average value that is calculated after assigning any cost driver values that are less than 15% of the maximum to the "Other" cost driver category. We assumed that a cost value that low reflects miscellaneous changes to the system rather than a significant cost driver upgrade. For example, in Table 1, the 46 \$K value for (R/S) of Magellan is less than 15% of 5,484 \$K of Voyager (N); therefore, this cost driver for Magellan is considered "Other". Consequently, the typical (R/S) cost driver value will be the average of that of Voyager (U), and Voyager (N) or 3,429 \$K. The numbers in brackets in Table 1 were handled this way. Note that Magellan has 770 \$K of miscellaneous costs in addition to the R/M [33] and R/S [46] included in 'Other' cost driver category.

2.4 Back Testing the Total Mission Cost Drivers Model

The total mission cost drivers model (Table 1) was compared with the actuals for the three missions: Voyager (U), Voyager (N) and Magellan as shown in Table 2. A comparison of the actual cost and costs predicted by Model A for the three missions can be seen in the Totals of Table 2. The difference in predicting individual mission costs ranges from 17% below to 18.9% above actual costs for Voyager (N) and Voyager (U), respectively. The costs estimated from the model are about 1.9% below that of actual costs for Magellan.

Table 2. Actual and Model A costs for three missions, 1987 \$K

Cost Drivers	Voyager (U)		Voyager (N)		Magellan	
	Actual	Model	Actual	Model	Actual	Model
M/O	955	755	677	755	634	755
R/M	2,032	1,306	580	1,306	0	0
R/S	1,374	3,429	5,484	3,429	0	0
D/L	2,647	3,808	6,566	3,808	2,211	3,808
VLBI	0	0	0	0	4,436	4,436
U/L	0	0	0	0	8,947	8,947
TEL	10,357	12,901	0	0	15,445	12,901
G/T	17,795	19,402	21,008	19,402	0	0
Other	700	1,095	1,735	1,095	849	1,095
Total	35,860	42,696	36,050	29,795	32,522	31,942

2.5 How To Use Model A: The Total Mission Cost Drivers Model

Model A is developed from historical cost data as an average of three space missions: Voyager (U), Voyager (N), and Magellan. For example, to estimate the total cost for a mission that has the following six cost drivers: R/M, R/S, VLBI, U/L, TEL and G/T, we look up the typical cost driver values in Table 1 and sum them. A summary is given in Table 3.

Table 3. Preparation costs predicted by Model A in 1987 \$M

Cost Drivers	Cost Predicted by Model A
R/M	1.3
R/S	3.4
VLBI	4.4
U/L	8.9
TEL	12.9
G/T	19.4
Total	50.3

Model A gives us the total DSN cost to prepare for a mission; but it does not give a profile of costs over time. Now, we will look at Model B that will give the cost profile over time.

3. MODEL B: THE COST DRIVERS TIME PROFILE MODEL

3.1 Development of Cost Drivers Time Profile Model

The average annual cost for each cost driver of the three missions, Voyager (U), Voyager (N), and Magellan is calculated and shown in Table 5 as actual (A) data. The average data for each cost driver is then regressed over time and the equation that best describes the data is chosen as shown in Table 4. In each equation of Table 4, Y_t is the cost in year t , ($t = 1, 2, \dots, n$); t is the number of the year in the life of the DSN preparation cost for a mission, n is the total years of the DSN preparation; and the total cost of the DSN preparation for a cost driver is $Y(\text{Total}) = \sum Y_t$.

Table 4. The best-fit equation for each cost driver

Cost Drivers	Model	R^2
(M/O)	$Y_t = 352 - 318t + 144t^2 - 18.6t^3$	99
(D/L)	$Y_t = -3,053 + 4,558t - 1,474t^2 + 139t^3$	82
(U/L)	$Y_t = 4,561 - 25t$ (for $t = 3$ and 4)	100
(TEL)	$Y_t = -4,114 + 5,938t - 1,011t^2$	81
(G/T)	$Y_t = -2,175 + 5,880t - 1,053t^2$	99
(R/M)	$Y_t = 104 + 229t - 48.1t^2$	90
(R/S)	$Y_t = 1,339 - 2,207t + 1,218t^2 - 165t^3$	98
(VLBI)	$Y_t = -792 + 860t$ (for $t = 3$ and 4)	100

3.2 Analysis of Model B: The Cost Drivers Time Model

The equations chosen for the cost drivers are: Linear for U/L and VLBI, Quadratic for TEL, G/T, and

R/M, and Cubic for M/O, D/L, and R/S. Figures 1 and 2 show the actual costs and those predicted by the equations for typical cost drivers.

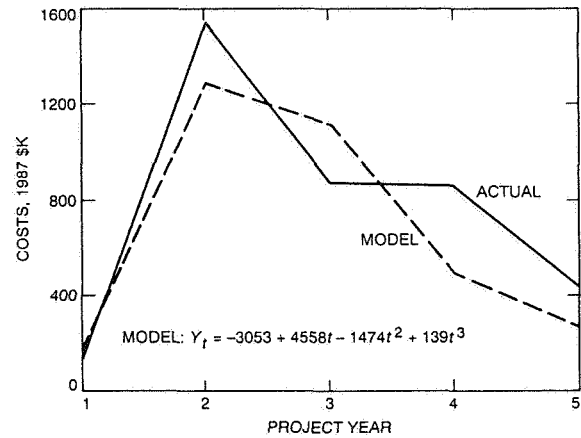


Figure 1. D/L (Downlink Frequency) Cost Driver

3.3 Back Testing Model B: The Cost Drivers Time Profile Model

Model B was checked with the three missions: Voyager (U), Voyager (N) and Magellan. Table 5 shows the average actual annual costs of the three missions as (A) data and costs predicted by the model as (M) data. Table 6 shows that the average cost per mission of 33.6 \$M as predicted by the model is 1.2 \$M below actual average cost of 34.8 \$M. The difference is about 3.4%. However, the difference in predicting total costs ranges from 22.5% below to 17.5% above actual costs to prepare for Voyager (N) and Voyager (U) respectively. The difference in predicting total cost to prepare for Magellan is 5%.

Table 5. Summary of actual average annual preparation costs for three missions and costs predicted by Model B, \$K (1987 \$). "A" = actual costs; "M" = Model B costs.

Year	M/O	D/L	U/L	TEL	G/T	R/M	R/S	VLBI	Other	Total
1 (A)	159	126	-	502	2,753	258	164	-	444	4,406
(M)	159	170	-	813	2,652	285	185	-	283	4,547
2 (A)	149	1,535	-	4,782	5,172	421	557	-	115	12,731
(M)	143	1,279	-	3,718	5,372	369	477	-	335	11,693
3 (A)	191	867	4,486	3,279	5,980	361	1,100	1,788	536	18,588
(M)	192	1,108	4,486	4,601	5,986	358	1,225	1,788	477	20,221
4 (A)	206	853	4,461	4,161	4,704	193	1,513	2,648	-	18,739
(M)	194	491	4,461	3,462	4,497	250	1,439	2,648	-	17,442
5 (A)	50	427	-	177	793	73	95	-	-	1,615
(M)	37	262	-	300	896	46	129	-	-	1,670
Total (A)	755	3,808	8,947	12,901	19,402	1,306	3,429	4,436	1,095	56,079
Total (M)	725	3,310	8,947	12,894	19,403	1,308	3,455	4,436	1,095	55,573
(M-A)	-30	-498	0	-7	1	2	26	0	0	-506

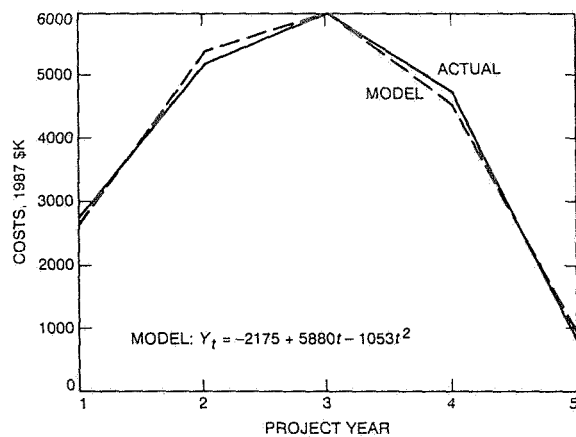


Figure 2. G/T (Antenna Gain/Noise Temperature) Cost Driver

3.4 How To Use Model B: The Cost Drivers Time Profile Model

As an example, to estimate the costs to prepare for five years of DSN modifications and enhancements that incur all nine cost drivers, we look up the model results in Table 5 and sum the predicted costs by the model. The results are shown in Table 7.

Table 6. Summary of the actual preparation costs for three missions, and the costs predicted by Model B, \$M (1987 \$)

Space Mission	Actual Preparation Cost, \$M	Model B Preparation Cost, \$M	Model B Minus Actual, Δ in \$M	Error, %, Δ/Actual
Voyager (U)	35.9	42.2	6.3	17.5
Voyager (N)	36.0	27.9	-8.1	-22.5
Magellan	32.5	30.8	-1.7	-5.0
Average for all missions	34.8	33.6	-1.2	-3.4

A second example is to estimate the total costs over time to prepare for five years of DSN modifications and enhancements that incur six cost drivers: R/M, R/S, VLBI, U/L, TEL and G/T. We look up the model results in Table 5 and sum the predicted costs by the model. The results are shown in Table 8.

4. EXTERNAL CHECK

4.1 Independent Missions Comparison

Model A was tested against two other independent missions: MJS and Viking. The project

Table 7. Estimate of preparation costs for a five-year, nine-cost-driver mission by Model B, \$K (1987 \$)

Year	Actual Cost-Driver Total Cost, \$K	Model B Cost-Driver Total Cost, \$K	Model Minus Actual, Δ in \$K	Error, %, Δ/Actual
1	4,406	4,547	141	3
2	12,731	11,693	-1,038	-8
3	18,588	20,221	1,633	9
4	18,739	17,442	-1,297	-7
5	1,615	1,670	55	3
Total	56,079	55,573	-506	-1

Mariner Jupiter/Saturn (MJS) incurred all major costdrivers that are covered in this paper [6]. From Table 1, the total cost for all the major cost drivers is 56.1 (1987 \$M). Based on a previous study [3], it was concluded that the MJS modification and enhancement of 10 years had two distinct phases, one for Jupiter and one for Saturn, each lasting five years. The MJS cost estimate is then twice that predicted for the five year calculation. That results in a predicted cost of 112.2 (1987 \$M) as compared to the actual cost of 97.5 (\$M) [7]. The difference is about 15%. The Viking project, which took five years of DSN modification, did not use VLBI; however, it used the other cost drivers [8]. The estimated total cost for Viking by model A is then 56,079 - 4,436 = 51,643 (1987 \$K) or about 51.6 (\$M) as compared to the actual cost of 49.7 (\$M) [7]. The difference is 3.8%.

Model B was also tested against MJS and Viking. The total actual cost for MJS was 97.5 (\$M). The MJS cost estimate by model B is also twice that predicted for the five year calculation, as explained above and shown in Table 5. That results in a predicted cost of 2 x 55.573 (\$M) or 111.15 (1987 \$M). The difference is about 14%. The Viking project did not

Table 8. Estimate of preparation costs for a five-year, six-cost-driver mission by Model B, \$M (1987 \$)

Cost Drivers	Cost Predicted by Model B
R/M	1.3
R/S	3.5
VLBI	4.4
U/L	8.9
TEL	13.0
G/T	19.4
Total	50.5

use VLBI, and thus the estimated total cost for Viking by model B is $55,573 - 4,436 = 51,137$ (1987 \$K) or about 51.1 (\$M) as compared to the actual cost of 49.7 (\$M). The difference is 3%. Model B was not compared with MJS and Viking on an annual basis since the actual annual detailed data is no longer available.

5. SUMMARY

A cost model has been presented to give estimates for future DSN modification and enhancement costs to prepare for future space missions. The model has two versions: A and B.

Version A is called the total mission cost drivers model (Model A), and Version B is called the cost drivers time profile model (Model B).

Model A estimates total DSN costs based on average DSN cost drivers from three space missions: Voyager (U), Voyager (N) and Magellan. The model is concerned with those cost drivers that are relevant to a mission, and thus is sensitive to mission objectives and uniqueness. Model A does a reasonable job of representing the actual costs for Voyager (U), Voyager (N) and Magellan. Based on our back-testing the actual three projects against the model, the results are in the range of 17% below to 19% above actual costs. Model A was also compared to two other independent projects, Mariner Jupiter/Saturn (MJS) and Viking. The model gave total cost estimates which range from 15% to 4% above actual total costs for MJS and Viking respectively.

Model B estimates the annual costs of each cost driver relevant to a mission and also total mission cost. The model is time and cost driver sensitive and thus will capture future mission costs dependence on both time and relevant cost drivers. Model B was also compared to the actual DSN modification and enhancement costs over time for Voyager (U), Voyager (N) and Magellan. Based on our back testing the actual three projects against the model, the results are in the range of 22.5% below to 17.5% above actual costs. Model B was also compared to MJS and Viking. The model gave total cost estimates which range from 14% to 3% above actual total costs for MJS and Viking respectively. Both Model A and Model B are applicable to missions that do not exceed five years of duration and that have the cost drivers discussed in this study.

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